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CHARM HADRONIC DECAY BRANCHING FRACTIONS FROM CLEO-C

PETER ONYISI
(for the CLEO Collaboration)
Cornell University, Ithaca, New York 14853, USA
ponyisi@lepp.cornell.edu

The CLEO-c experiment at the CESR e^+e^- storage ring has collected data with $E_{\rm cm} =$ 3.77 GeV and $E_{\rm cm} \sim$ 4.17 GeV to study the decays of charmed mesons. This paper discusses results on the hadronic branching fractions of the D^0, D^+, and D_s^+.

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1. Introduction

The branching fractions of all-hadronic decays of the lightest charmed mesons are of interest for several reasons. The absolute branching fractions of the D^0, D^+, and D_s^+ mesons[a] serve to normalize other charm meson decays and decay chains through charm quarks. Due to the large branching fraction of $b \to c$, charm branching fractions normalize many processes in b physics. Inclusive decay rates of charmed mesons to final states including easily-identifiable particles can also be used to disentangle particle content.

Hadronic charm decays are also of intrinsic interest in understanding the dynamics of the strong force. Phase shifts between different processes can be probed by measuring the branching fractions of final states that interfere or are related by isospin symmetry.

2. Experimental Methods

The CLEO-c experiment at the CESR e^+e^- collider has collected 281 pb^{-1} of data at center of mass energy $E_{\rm cm} = 3.77$ GeV and approximately 200 pb^{-1} with $E_{\rm cm}$ near 4.17 GeV. The 3.77 GeV dataset, taken at the peak of the $\psi(3770)$ resonance, contains approximately 1 million $e^+e^- \to D^0\overline{D}^0$ and 0.8 million $e^+e^- \to D^+D^-$

[a] Except where stated, mention of a particle or decay implies the charge conjugate particle or process as well.

events. The 4.17 GeV dataset, taken at an energy that optimizes the production of $D_s^{*\pm}D_s^{\mp}$ events with cross section ~ 1 nb, is primarily used for studies of D_s^+ mesons.

For D^0 and D^+ mesons at 3.77 GeV, and for D_s^+ mesons at 4.17 GeV, the production of a charmed meson is always associated with the production of its antiparticle, as 3.77 GeV and 4.17 GeV are below the $DD\pi$ and D_sDK thresholds, respectively. Reconstruction of "tag" D^0, D^+, or D_s^+ candidates thus provides a clean sample of a known number of decays of the antiparticle and enables powerful methods for measuring absolute branching fractions as detailed below.

Analyses of the 3.77 GeV data use the kinematic variables ΔE and $m_{\rm BC}$, defined as[b] $\Delta E \equiv E_{\rm cand} - E_{\rm beam}$ and $m_{\rm BC} \equiv \sqrt{E_{\rm beam}^2 - |\vec{p}_{\rm cand}|^2}$, where $E_{\rm cand}$, $\vec{p}_{\rm cand}$ are the energy and momentum of the D candidate. For equal-mass particles of mass M produced in a two-body process, ΔE will peak at zero, and $m_{\rm BC}$ will peak at M with better resolution than the invariant mass. D candidates are required to have ΔE consistent with zero within roughly three standard deviations.

For analyses at 4.17 GeV, the $m_{\rm BC}$ variable is used along with the invariant mass of the D candidate. At this energy $m_{\rm BC}$ functions as a nearly energy-independent proxy for momentum, and separates states produced in different two-body processes. The D_s^+ produced from D_s^{*+} decays are boosted slightly relative to the nominal two-body momentum; the consequent smearing in $m_{\rm BC}$ is accounted for in the selection requirements.

3. Absolute Hadronic Branching Fractions

Precise measurements of charm meson branching fractions are often made as branching ratios to easy-to-identify and frequent all-hadronic final states, especially $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$. Uncertainties in these normalizing branching fractions thus propagate to many other modes. Additionally, measurements of decay chains with D mesons in the final state usually involve a normalizing D decay which must be removed to obtain branching fractions for the intermediate states. Reducing the uncertainties in these normalizing modes is a primary goal of CLEO-c. Before CLEO-c input, the relative uncertainties in these branching fractions were about 3%, 6%, and 13% for D^0, D^+, and D_s^+, respectively[1,2].

To measure the absolute branching fractions CLEO-c uses a technique pioneered by the the MARK III collaboration[3,4]. Single D candidates are reconstructed, regardless of the rest of the event; these are called "single tags" (ST). Full reconstruction of a $D\overline{D}$ pair is also attempted, and candidates are referred to as "double tags" (DT). Ratios of ST yields to each other give precise branching ratios, while ratios of DT to ST yields give information on the absolute branching fractions. CLEO-c measures ST yields in three, six, and four decay modes for D^0, D^+, and

[b]In this paper, $c = 1$, and mass and momentum are measured in units of energy.

D_s^+ respectively (separating charge conjugate states), and in 9, 36, and 15 DT final states for $D^0\overline{D}^0$, D^+D^-, and $D_s^+D_s^-$ respectively (one $D_s^+D_s^-$ double tag mode, $\pi^+\pi^+\pi^-/\pi^-\pi^-\pi^+$, is dropped due to continuum background). Fits are performed to the observed yields in terms of the total number of produced D pairs, $N_{D\overline{D}}$, and the branching fraction for each mode[5].

The results here are based on 56 pb^{-1} of 3.77 GeV data for D^0 and D^+ and 75 pb^{-1} of $\sim$ 4.17 GeV data for D_s^+. The D^0 and D^+ results are published in Ref. 6; the D_s^+ results are preliminary. The branching fractions obtained are listed in Table 1.

Table 1. Branching fractions for D^0 and D^+ (from 56 pb^{-1}) and D_s^+ (from 75 pb^{-1}, preliminary). Uncertainties are statistical and systematic, respectively.

Branching Fraction	Fitted Value (%)
$\mathcal{B}(D^0 \to K^-\pi^+)$	$3.91 \pm 0.08 \pm 0.09$
$\mathcal{B}(D^0 \to K^-\pi^+\pi^0)$	$14.9 \pm 0.3 \pm 0.5$
$\mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)$	$8.3 \pm 0.2 \pm 0.3$
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	$9.5 \pm 0.2 \pm 0.3$
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+\pi^0)$	$6.0 \pm 0.2 \pm 0.2$
$\mathcal{B}(D^+ \to K_S^0\pi^+)$	$1.55 \pm 0.05 \pm 0.06$
$\mathcal{B}(D^+ \to K_S^0\pi^+\pi^0)$	$7.2 \pm 0.2 \pm 0.4$
$\mathcal{B}(D^+ \to K_S^0\pi^+\pi^+\pi^-)$	$3.2 \pm 0.1 \pm 0.2$
$\mathcal{B}(D^+ \to K^+K^-\pi^+)$	$0.97 \pm 0.04 \pm 0.04$
$\mathcal{B}(D_s^+ \to K_S^0K^+)$	$1.28^{+0.13}_{-0.12} \pm 0.07$
$\mathcal{B}(D_s^+ \to K^-K^+\pi^+)$	$4.54^{+0.44}_{-0.42} \pm 0.25$
$\mathcal{B}(D_s^+ \to K^-K^+\pi^+\pi^0)$	$4.83^{+0.49}_{-0.47} \pm 0.46$
$\mathcal{B}(D_s^+ \to \pi^+\pi^+\pi^-)$	$1.02^{+0.11}_{-0.10} \pm 0.05$

CLEO-c does not report a $D_s^+ \to \phi\pi^+$ branching fraction. Such events with $\phi \to K^-K^+$ are included in the $D_s^+ \to K^-K^+\pi^+$ branching fraction. Previous experiments have evaluated cuts and efficiencies assuming that all the $K^-K^+\pi^+$ signal in the ϕ mass region is in fact from the $\phi\pi^+$ intermediate state. However there is strong evidence[7,8] for a broad scalar contribution underneath the ϕ which will contribute differently to a "$\phi\pi^+$" signal depending on the specific selection requirements chosen, possibly varying up to 10% between measurements. Since CLEO-c measurements will soon exceed this level of precision, the need for better-defined reference branching fractions has been recognized. The long-term solution for precision experiments wishing to use a "$\phi\pi^+$" signal will be to couple the inclusive $K^-K^+\pi^+$ branching fraction with Monte Carlo incorporating Dalitz analysis of this decay.

4. Cabibbo–Suppressed D^0 and D^+ Decays

The branching fractions of the Cabibbo–suppressed decays of D^0 and D^+ to multi-pion final states are poorly measured, especially for modes with π^0 mesons. Knowledge of these branching fractions allows better understanding and simulation of backgrounds to other decays, in particular those involving K_S^0 mesons. Multi-pion decays also give information on intermediate resonant states (through, *e.g.,* $\eta \to \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$). Finally, the three decay modes $D^0 \to \pi^+\pi^-$, $D^0 \to \pi^0\pi^0$, and $D^+ \to \pi^+\pi^0$ form an isospin triangle that permits the extraction of the phase difference between the $\Delta I = 3/2$ and $\Delta I = 1/2$ amplitudes (A_2 and A_0, respectively).

In this analysis[9], which uses the full 281 pb^{-1} dataset, candidates are reconstructed in seven D^0 and five D^+ all-pion final states. Vetoes on the invariant mass of $\pi^+\pi^-$ and $\pi^0\pi^0$ pairs are applied to remove contamination from K_S^0 decays. Branching ratios are obtained relative to $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$. First observations are made of four inclusive final states and two intermediate states; limits are placed on the inclusive $D^0 \to \pi^0\pi^0\pi^0$ decay and three intermediate states. The results are summarized in Table 2. The ratio of the two isospin amplitudes for $D \to \pi\pi$ is found to be:

$$|A_2/A_0| = 0.420 \pm 0.014 \pm 0.016; \qquad \arg(A_2/A_0) = (86.4 \pm 2.8 \pm 3.3)^\circ$$

5. Decays of D^+ to $K_S^0\pi^+$ and $K_L^0\pi^+$

The Cabibbo–favored (CF) decay of a D^0 or D^+ meson to a state with a neutral kaon includes a $\overline{K}^0$. However there are also doubly-Cabibbo–suppressed (DCS) decays where the final state instead has a K^0. The $D \to K^0X$ amplitude will interfere

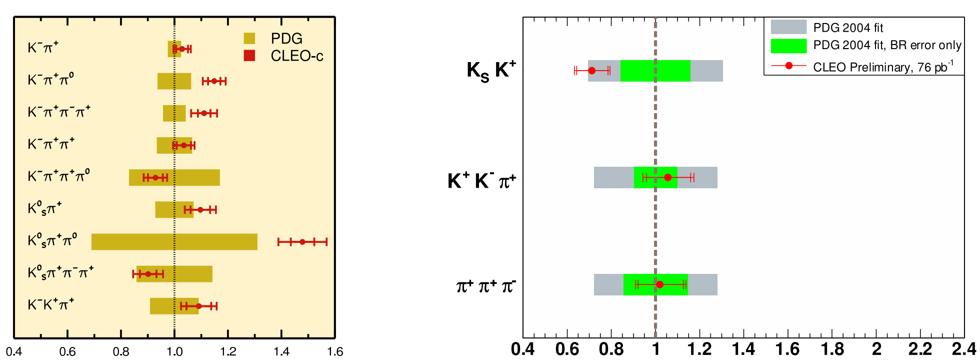

Fig. 1. Ratios of CLEO-c results for absolute D^0 and D^+ (left) and D_s^+ (right) branching fractions to the PDG 2004 fits. The smaller and larger CLEO-c error bars are statistical and systematic uncertainties, respectively. The bars for the D_s^+ results marked "PDG 2004 fit, BR error only" are the uncertainty on the branching fraction arising from the branching ratio to $D_s^+ \to \phi\pi^+$. The $D_s^+ \to K^-K^+\pi^+\pi^0$ mode is not included as it is the first measurement of the inclusive branching fraction to that final state.

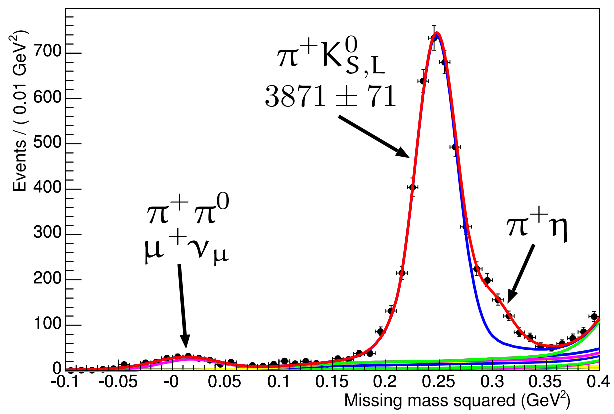

Fig. 2. Missing mass squared for events in the $D^+ \to K^0_{S,L}\pi^+$ analysis.

with the $D \to \overline{K}^0 X$ amplitude with the sign of the interference being opposite for the observed states K^0_S and K^0_L. The branching fractions of D mesons to K^0_S and K^0_L should thus in general be different, with an asymmetry of the order of $\tan^2\theta_C$ (enhanced over the DCS rate because this is an interference effect)[10]. This will be modified by the unknown phase between the CF and DCS amplitudes in each mode.

CLEO-c obtains absolute branching fractions for the process $D^+ \to K^0_{S,L}\pi^+$ from the full 281 pb^{-1} sample ("$K^0_{S,L}$" represents the sum of K^0_S and K^0_L contributions to a neutral kaon branching fraction). Six decay modes are used to find tag $D^\pm$ candidates. A pion of the opposite charge, putatively from the $D^\mp$ decay, is then searched for, and the missing mass squared of the $D^\pm\pi^\mp$ system is computed. A clear peak at the kaon mass squared is seen. Extra peaking contributions are seen from two-body modes with charged pions and muons in the final state, and small smooth backgrounds from three-body modes and combinatoric background are also accounted for, with shapes obtained from Monte Carlo simulations.

A measurement of $\mathcal{B}(D^+ \to K^0_{S,L}\pi^+)$ can be combined with the directly-measured $\mathcal{B}(D^+ \to K^0_S\pi^+)$ from Table 1 to obtain an asymmetry. The analysis yields the following preliminary results:

$$\mathcal{B}(D^+ \to K^0_{S,L}\pi^+) = (3.055 \pm 0.057 \pm 0.158)\%$$

$$\frac{\mathcal{B}(D^+ \to K_L\pi^+) - \mathcal{B}(D^+ \to K_S\pi^+)}{\mathcal{B}(D^+ \to K^0_{S,L}\pi^+)} = -0.01 \pm 0.04 \pm 0.07$$

$$\mathcal{B}(D^+ \to \eta\pi^+) = (0.391 \pm 0.031 \pm 0.033)\%$$

No significant asymmetry is observed in this decay mode. This could result from the phase between the CF and DCS amplitudes being $\approx 90°$. The branching fraction for $D^+ \to \eta\pi^+$ agrees with that obtained from the multi-pion analysis.

6. Inclusive Decays of Charmed Mesons to η, η', and ϕ

Because a Cabibbo–favored decay of a D_s^+ meson has an $s\bar{s}$ quark pair, while Cabibbo–favored D^0 and D^+ decays generally do not, one expects that mesons with large $s\bar{s}$ content will be produced more often in D_s^+ decay than in D^0 and D^+ decays. This difference can be used, for example, to estimate the rate of B_s production at the $\Upsilon(5S)$ resonance by exploiting the large $B_s \to D_s X$ branching fraction.

CLEO-c has preliminary measurements of inclusive rates of the production of η, η', and ϕ mesons in D^0, D^+, and D_s^+ decays using the full 281 pb^{-1} dataset at 3.77 GeV and 71 pb^{-1} of 4.17 GeV data. D^0, D^+, and D_s^+ candidates are reconstructed as tags, and the remaining showers and tracks are used to reconstruct mesons in the $\eta \to \gamma\gamma$, $\eta' \to \pi^+\pi^-\eta \to \pi^+\pi^-\gamma\gamma$, and $\phi \to K^-K^+$ decay modes. Sidebands in ΔE (for D^0 and D^+) and $m_{\rm BC}$ (for D_s^+) are used to subtract peaking combinatoric backgrounds.

The results are listed in Table 3. The D_s^+ branching fractions to these mesons are significantly larger than those for D^0 and D^+, as expected.

7. Summary

The CLEO-c experiment has recorded 281 pb^{-1} of e^+e^- collisions at 3.77 GeV and 200 pb^{-1} near 4.17 GeV (of the latter, $\sim$ 75 pb^{-1} is used for the results presented here). Using these data branching fractions for many decay modes of the D^0, D^+, and D_s^+ mesons have been obtained with precision comparable to or exceeding the world average of previous measurements, and the absolute scale of these decays has been established using the unique kinematics of threshold production. CLEO-c intends to increase these datasets to roughly three times their current size.

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Table 2. Branching fractions using 281 pb^{-1} for D^0 and D^+ decays into all-pion final states. Uncertainties are statistical, systematic, uncertainty on reference decay branching fraction, and effects of CP correlation (D^0 only).

Mode	$\mathcal{B}$ (10^{-3})	PDG 2004 (10^{-3})
$D^0 \to \pi^+\pi^-$	$1.39 \pm 0.04 \pm 0.04 \pm 0.03 \pm 0.01$	1.38 ± 0.05
$D^0 \to \pi^0\pi^0$	$0.79 \pm 0.05 \pm 0.06 \pm 0.01 \pm 0.01$	0.84 ± 0.22
$D^0 \to \pi^+\pi^-\pi^0$	$13.2 \pm 0.2 \pm 0.5 \pm 0.2 \pm 0.1$	11 ± 4
$D^0 \to \pi^+\pi^+\pi^-\pi^-$	$7.3 \pm 0.1 \pm 0.3 \pm 0.1 \pm 0.1$	7.3 ± 0.5
$D^0 \to \pi^+\pi^-\pi^0\pi^0$	$9.9 \pm 0.6 \pm 0.7 \pm 0.2 \pm 0.1$	
$D^0 \to \pi^+\pi^+\pi^-\pi^-\pi^0$	$4.1 \pm 0.5 \pm 0.2 \pm 0.1 \pm 0.0$	
$D^0 \to \omega\pi^+\pi^-$	$1.7 \pm 0.5 \pm 0.2 \pm 0.0 \pm 0.0$	
$D^0 \to \eta\pi^0$	$0.62 \pm 0.14 \pm 0.05 \pm 0.01 \pm 0.01$	
$D^0 \to \pi^0\pi^0\pi^0$	< 0.35 (90% CL)	
$D^0 \to \omega\pi^0$	< 0.26 (90% CL)	
$D^0 \to \eta\pi^+\pi^-$	< 1.9 (90% CL)	
$D^+ \to \pi^+\pi^0$	$1.25 \pm 0.06 \pm 0.07 \pm 0.04$	1.33 ± 0.22
$D^+ \to \pi^+\pi^+\pi^-$	$3.35 \pm 0.10 \pm 0.16 \pm 0.12$	3.1 ± 0.4
$D^+ \to \pi^+\pi^0\pi^0$	$4.8 \pm 0.3 \pm 0.3 \pm 0.2$	
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	$11.6 \pm 0.4 \pm 0.6 \pm 0.4$	
$D^+ \to \pi^+\pi^+\pi^+\pi^-\pi^-$	$1.60 \pm 0.18 \pm 0.16 \pm 0.06$	1.73 ± 0.23
$D^+ \to \eta\pi^+$	$3.61 \pm 0.25 \pm 0.23 \pm 0.12$	3.0 ± 0.6
$D^+ \to \omega\pi^+$	< 0.34 (90% CL)	

Table 3. Preliminary branching fractions for D^0, D^+, and D_s^+ decays into inclusive final states with η, η', and ϕ mesons. Results use 281 pb^{-1} of data for D^0 and D^+ and 71 pb^{-1} for D_s^+.

Meson	$\mathcal{B}(D \to \phi X)$ (%)	$\mathcal{B}(D \to \eta X)$ (%)	$\mathcal{B}(D \to \eta' X)$ (%)
D^0	$1.0 \pm 0.1 \pm 0.1$	$9.4 \pm 0.4 \pm 0.6$	$2.6 \pm 0.2 \pm 0.2$
D^+	$1.1 \pm 0.1 \pm 0.2$	$5.7 \pm 0.5 \pm 0.5$	$1.0 \pm 0.2 \pm 0.1$
D_s^+	$15.1 \pm 2.1 \pm 1.5$	$32.0 \pm 5.6 \pm 4.7$	$11.9 \pm 3.3 \pm 1.2$

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